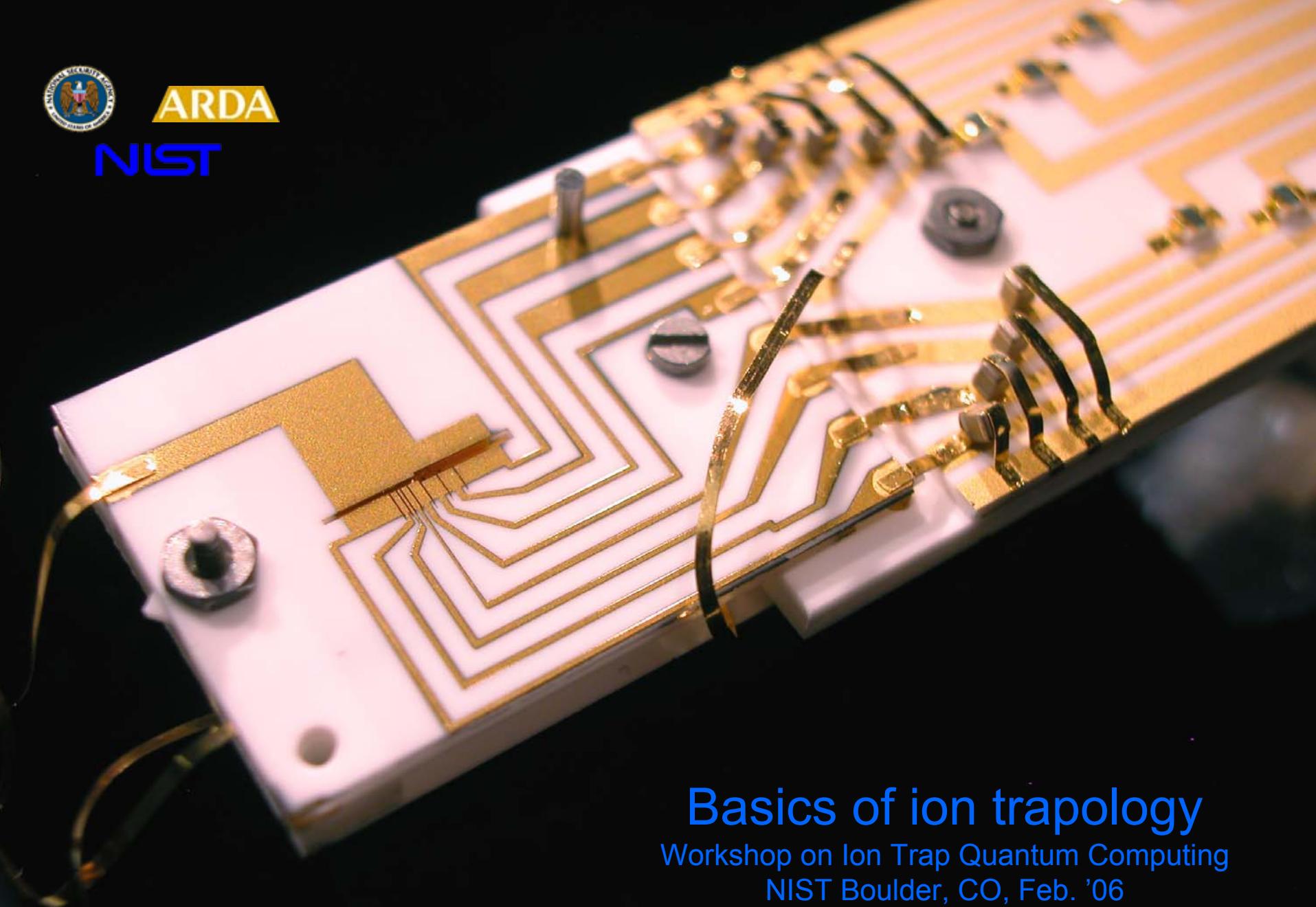




ARDA

NIST

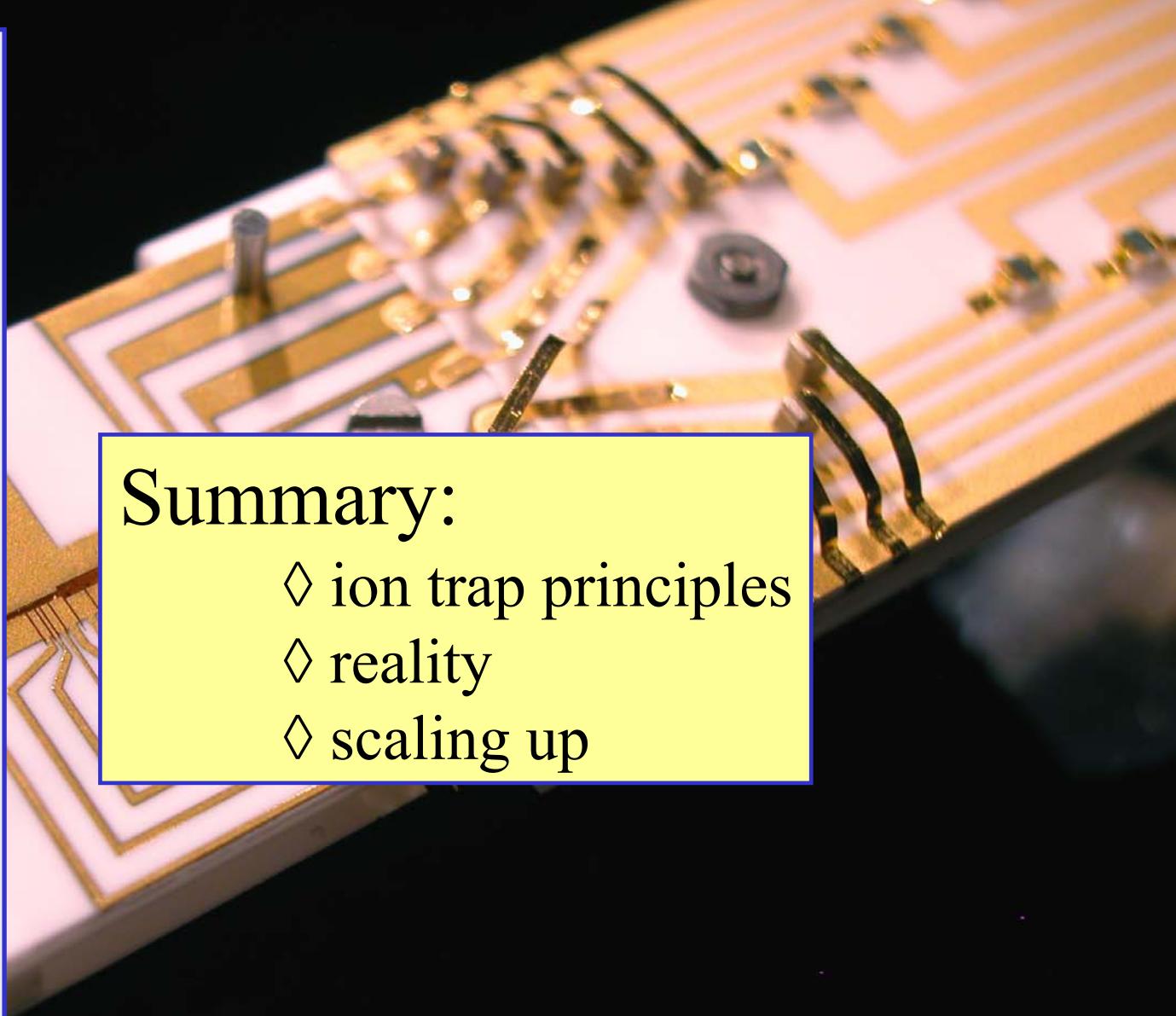


Basics of ion trapology

Workshop on Ion Trap Quantum Computing
NIST Boulder, CO, Feb. '06
D. J. Wineland

Trapped ion groups pursuing Quantum Information Processing (QIP):

Aarhus
Barcelona
Garching (MPQ)
Innsbruck
LANL
London (Imperial)
McMaster (Ontario)
Michigan
MIT
NIST
Osaka University
Oxford
Siegen
Simon Fraser
Sussex
Teddington (NPL)
Ulm
Washington (U. W.)

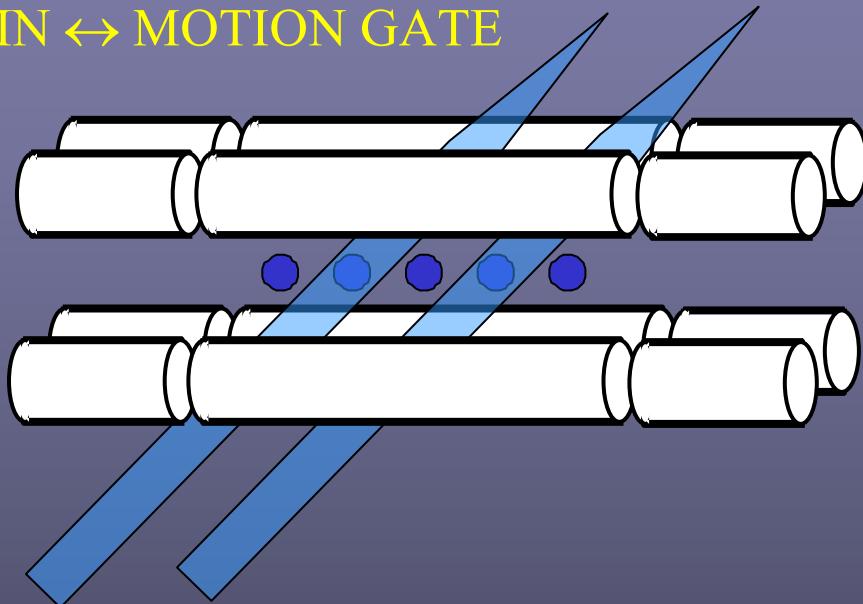


Summary:

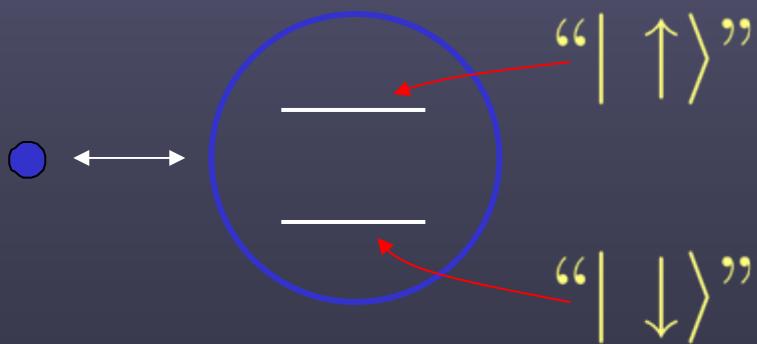
- ◊ ion trap principles
- ◊ reality
- ◊ scaling up

Atomic Ion QIP: Basic Idea: Ignacio Cirac, Peter Zoller, '95

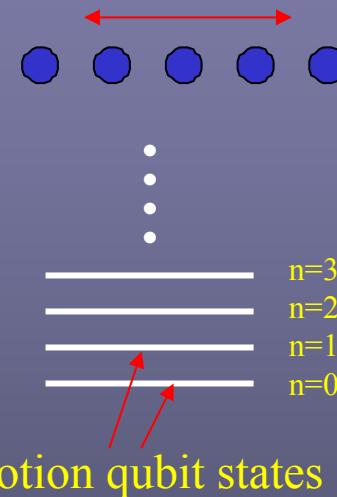
SPIN → MOTION MAP
SPIN ↔ MOTION GATE



Internal-state qubit



Motion “data bus”
(e.g., center-of-mass mode)



Want motion cold!

Ion trapping basics

“**Earnshaw’s theorem**” \cong In a charge free region, cannot confine a charged particle with static electric fields.

Proof: (1) For confinement, must have $(\partial^2(q\Phi)/\partial^2x_i)_{\text{trap location}} > 0$ ($x_i \in \{x, y, z\}$)
(2) Laplace’s equation: $\nabla^2\Phi = 0$, cannot (simultaneously) satisfy condition for all x_i .

Solution 1: Penning trap:

$$q\Phi \propto U_0 [2z^2 - x^2 - y^2], \mathbf{B} = B_0 \mathbf{z}$$

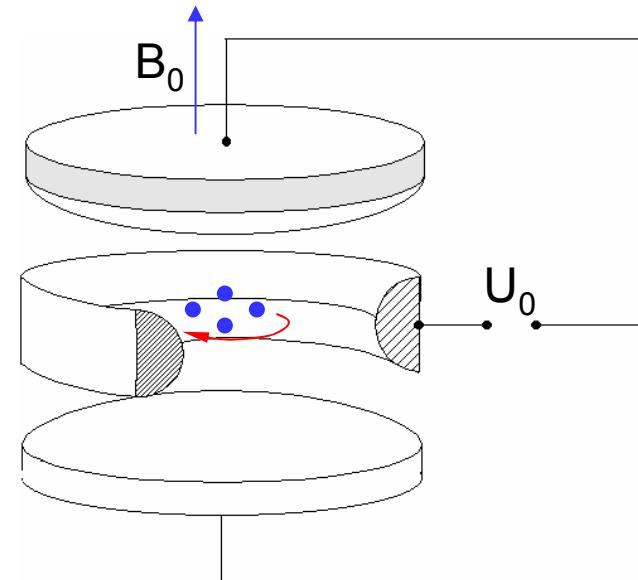
ion addressing? gates?

Ciaramicoli, Marzoli, Tombesi, PRL **91**, 017901 (2003))

Stahl *et al.*, Eur. Phys. J. D **32**, 139 (2005)

Castrejón-Pita, Thompson, PRA **72**, 013405 (2005)

see posters M03, M16, T06



Solution 2: RF-Paul trap:

$$\Phi = (\alpha x^2 + \beta y^2 + \gamma z^2) V_0 \cos \Omega t + U_0 (\alpha' x^2 + \beta' y^2 + \gamma' z^2)$$
$$[\alpha + \beta + \gamma = \alpha' + \beta' + \gamma' = 0] \quad (\text{Laplace})$$

Books on ion traps:

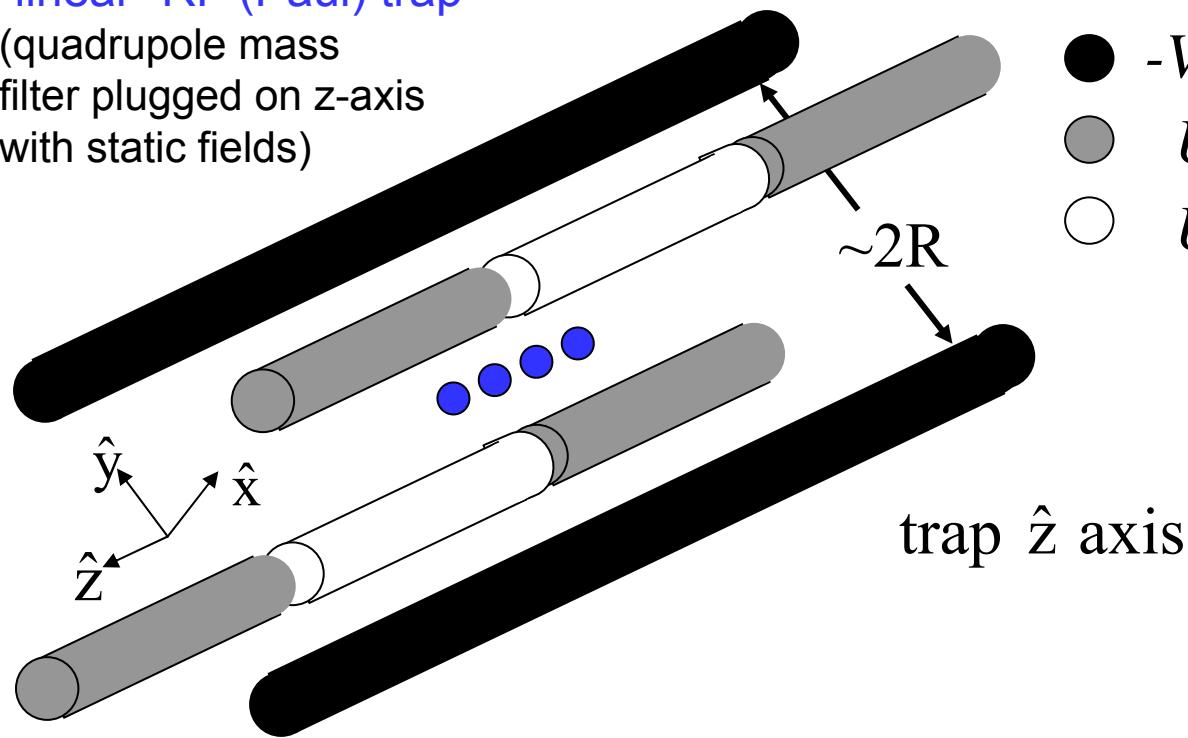
P.K. Ghosh, *Ion Traps* (Clarendon, Oxford, 1995).

F. G. Major, V. N. Gheorghe, and G. Werth, *Charged Particle Traps* (Springer, 2005).

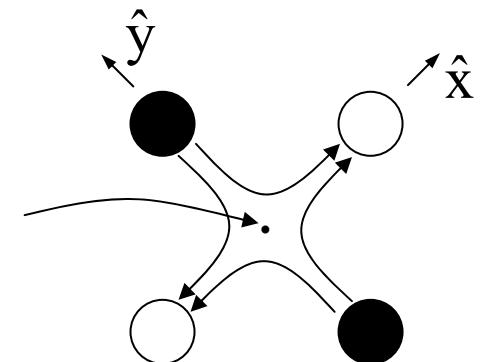
Special case:

“linear” RF (Paul) trap

(quadrupole mass filter plugged on z-axis with static fields)



- $-V_0 \cos \Omega_T t$
- U_o
- U_c



end view

near center of trap:

$$\Phi = \frac{(x^2 - y^2)}{2R^2} V_0 \cos \Omega_T t + \frac{(U_x x^2 + U_y y^2 + U_z z^2)}{2R^2},$$

$$\boxed{\sum_{i=x,y,z} U_i = 0}$$

$$U_x = \alpha_{xo} U_o + \alpha_{xc} U_c, \quad U_y = \alpha_{yo} U_o + \alpha_{yc} U_c, \quad U_z = \kappa(U_o - U_c)$$

(In practice, obtain α 's and κ numerically)

$$\Phi = \frac{(x^2 - y^2)}{2R^2} V_0 \cos \Omega_T t + \frac{(U_x x^2 + U_y y^2 + U_z z^2)}{2R^2}$$

$$\sum_{i=x,y,z} U_i = 0$$

Equations of motion

(classical treatment adequate) $\vec{\mathbf{F}} = m\vec{\mathbf{a}} \implies$

Mathieu equation

$$\frac{d^2 x_i}{d\xi^2} + [a_i - 2q_i \cos 2\xi] x_i = 0 \quad (i \in \{x, y, z\}) \quad (2)$$

$$a_i \equiv 4qU_i/m\Omega_T^2 R^2, \quad \xi \equiv \Omega_T t/2$$

$$q_x = -q_y \equiv -2qV_0/m\Omega_T^2 R^2, \quad q_z = 0$$

z-motion, $q_z = 0$ (static harmonic well)

$$\omega_z = (qU_z/mR^2)^{1/2} = \sqrt{a_z}\Omega_T/2$$

x,y motion, Mathieu equation:

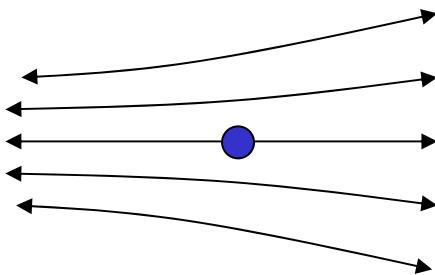
$$x_i(\xi) = A e^{i\beta_i \xi} \sum_{n=-\infty}^{\infty} C_{2n} e^{i2n\xi} + B e^{-i\beta_i \xi} \sum_{n=-\infty}^{\infty} C_{2n} e^{-i2n\xi} \quad (i \in \{x, y\})$$

plug into (2), find (recursion relation for) C_{2n} .

β_i real for certain ranges
of q_i , a_i (stability diagrams)

Heuristic approach: “pseudo-potential” approximation

$$\vec{E}(\vec{x}, t) = \vec{E}(\vec{x}) \cos \Omega_T t$$



- assume mean ion position changes negligibly in duration $2\pi/\Omega_T$

$$\vec{x} = \langle \vec{x} \rangle + \vec{x}_\mu$$

$$m \frac{\partial^2 \vec{x}_\mu}{\partial t^2} = q \vec{E}(\langle \vec{x} \rangle) \cos \Omega_T t \Rightarrow \vec{x}_\mu = -\frac{q \vec{E}(\langle \vec{x} \rangle)}{m \Omega_T^2} \cos \Omega_T t \text{ “micromotion”}$$

Calculate avg. force $\langle \vec{F} \rangle$ over one RF cycle. Then $U_{pseudo} = - \int \langle \vec{F} \rangle \cdot d\vec{x}$

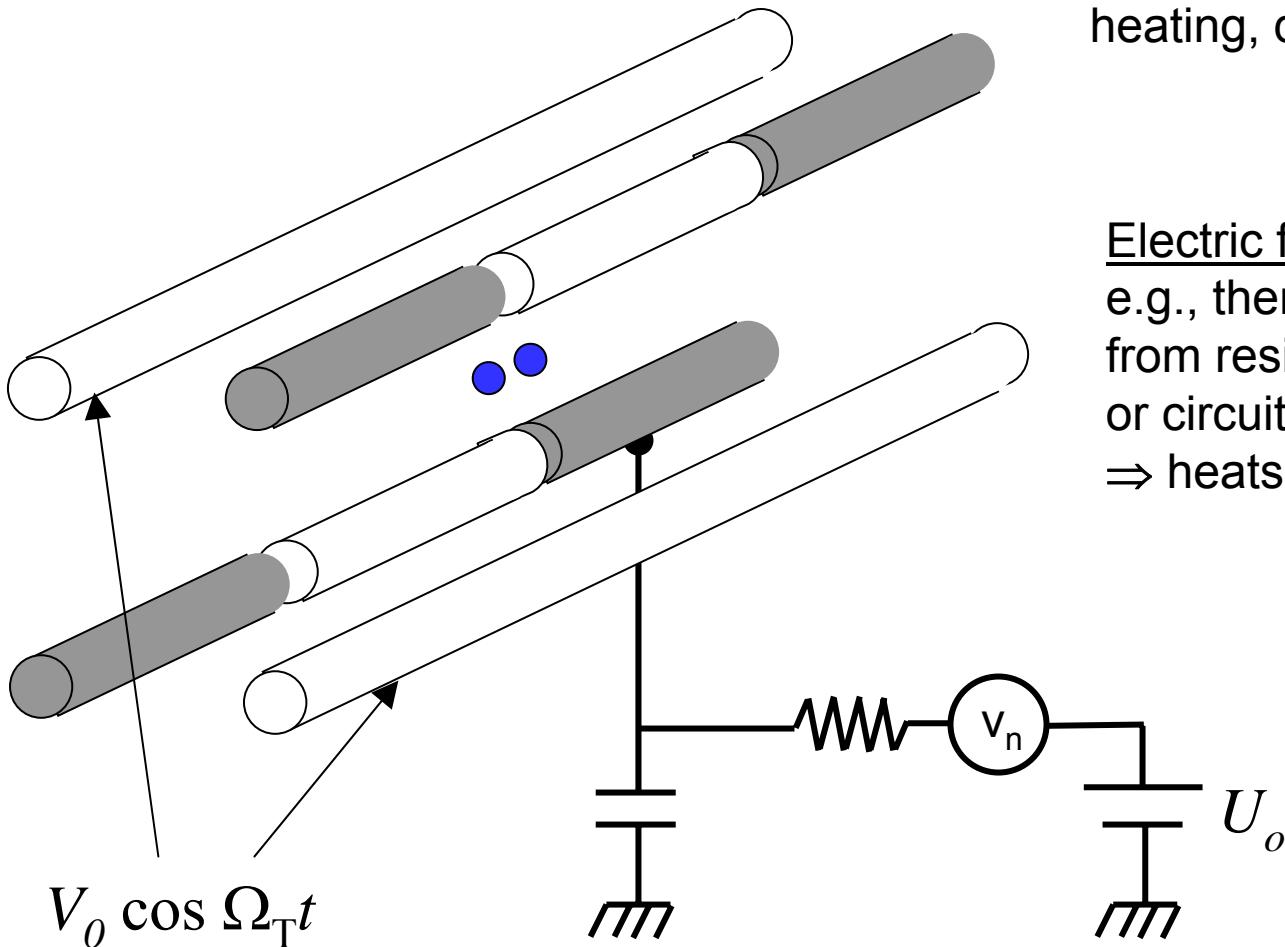
- for linear RF trap,

$$U_{pseudo} = \frac{q^2 V_0^2}{2m^2 \Omega_T^2 R^4} (x^2 + y^2) = \frac{1}{2} m \omega_{x,y}^2 (x^2 + y^2) \quad \omega_{x,y} = \frac{q V_0}{\sqrt{2} m \Omega_T R^2}$$

$$x_i(t) \simeq \underbrace{X_{i0} \cos \omega_i t}_{\text{“secular” motion}} \left[1 + \underbrace{\frac{q_i}{2} \sin \Omega_T t}_{\text{“micromotion”}} \right]$$

agrees with
Mathieu equation
in limit $|a_i|, q_i^2 \ll 1$
($\omega_i \ll \Omega_T$)

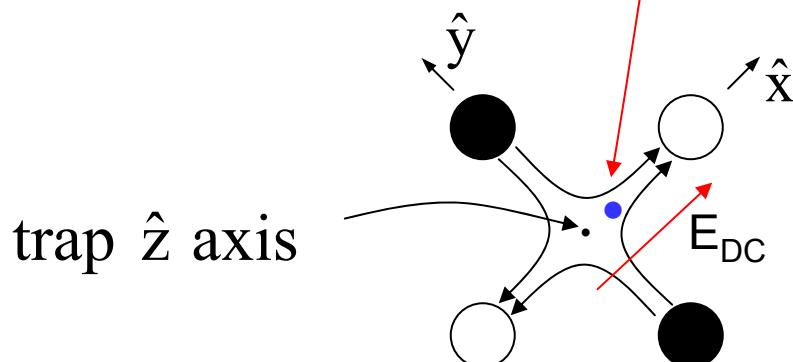
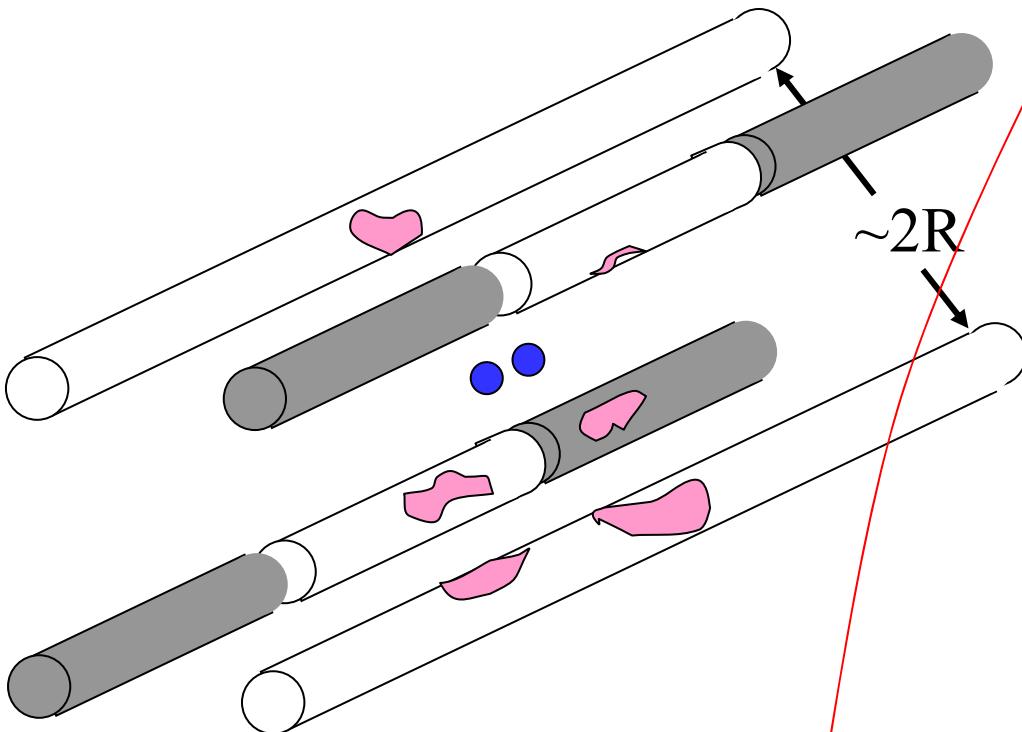
(some) ion-trap realities



RF absorption (lossy dielectrics)
heating, dimension changes,...

Electric field noise:
e.g., thermal electronic noise
from resistance in electrodes
or circuitry (Johnson noise)
⇒ heats ion motion

(some) ion-trap realities



trap \hat{z} axis

recall, that ideally

$$x_i(t) \simeq X_{i0} \cos \omega_i t + [X_{i0} \cos \omega_i t] \frac{q_i}{2} \sin \Omega_T t$$

Static “contact” or “patch” potentials:

push ions away from trap axis
⇒ micromotion $x_\mu \sin \Omega_T t$
reduces laser beam interaction

Fluctuating patch fields:

causes heating of ion motion (at ω_i)

Source: unknown!

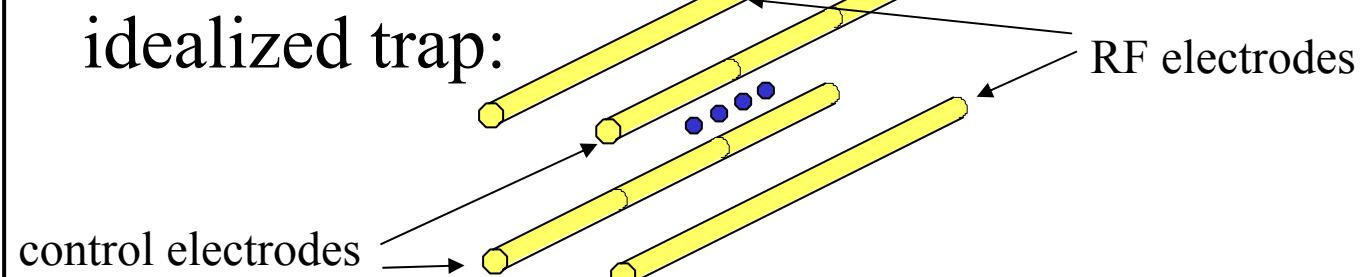
(mobile electrons on oxide layers,..... ??)

$$x_\mu = X_{displacement} \frac{q_i}{2} \sin \Omega_T t$$

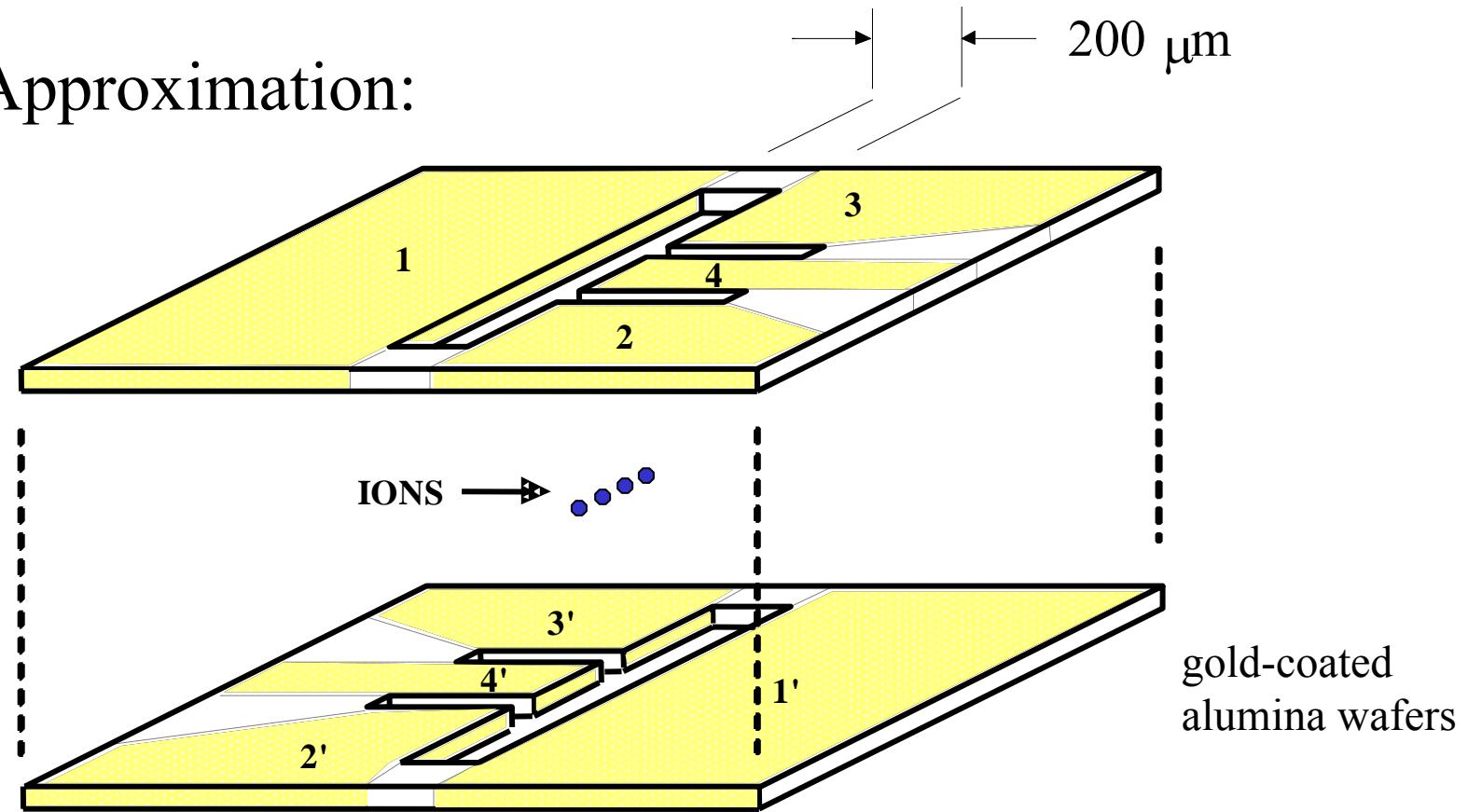
Trap fabrication

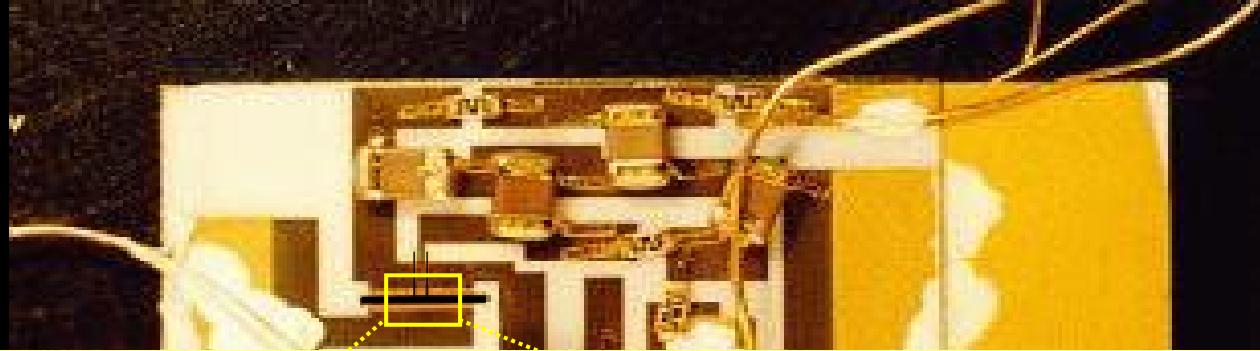
(Gate speed $\propto \omega_{\text{motion}}$
 $\propto (\text{dimensions})^{-2}$),

\Rightarrow want trap small

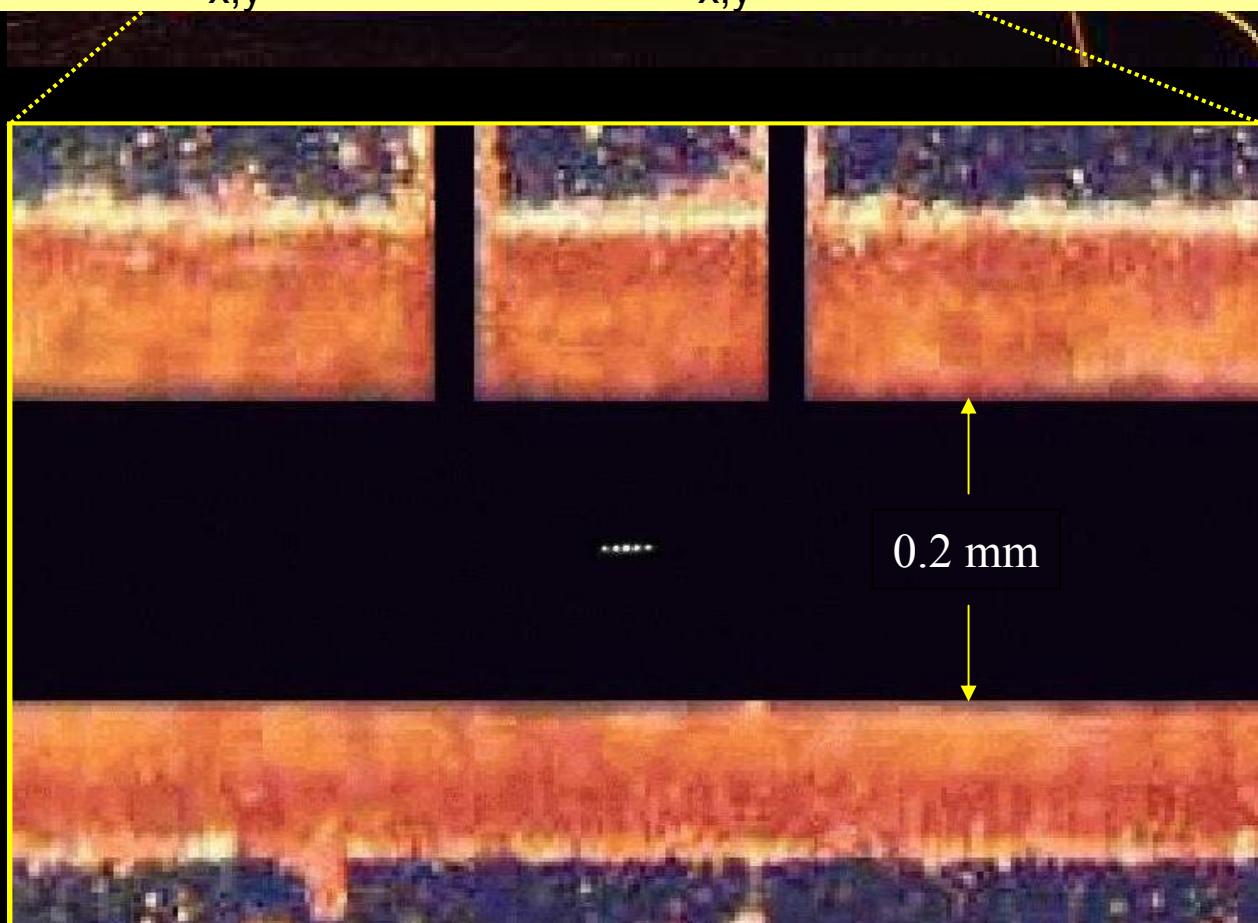


Approximation:

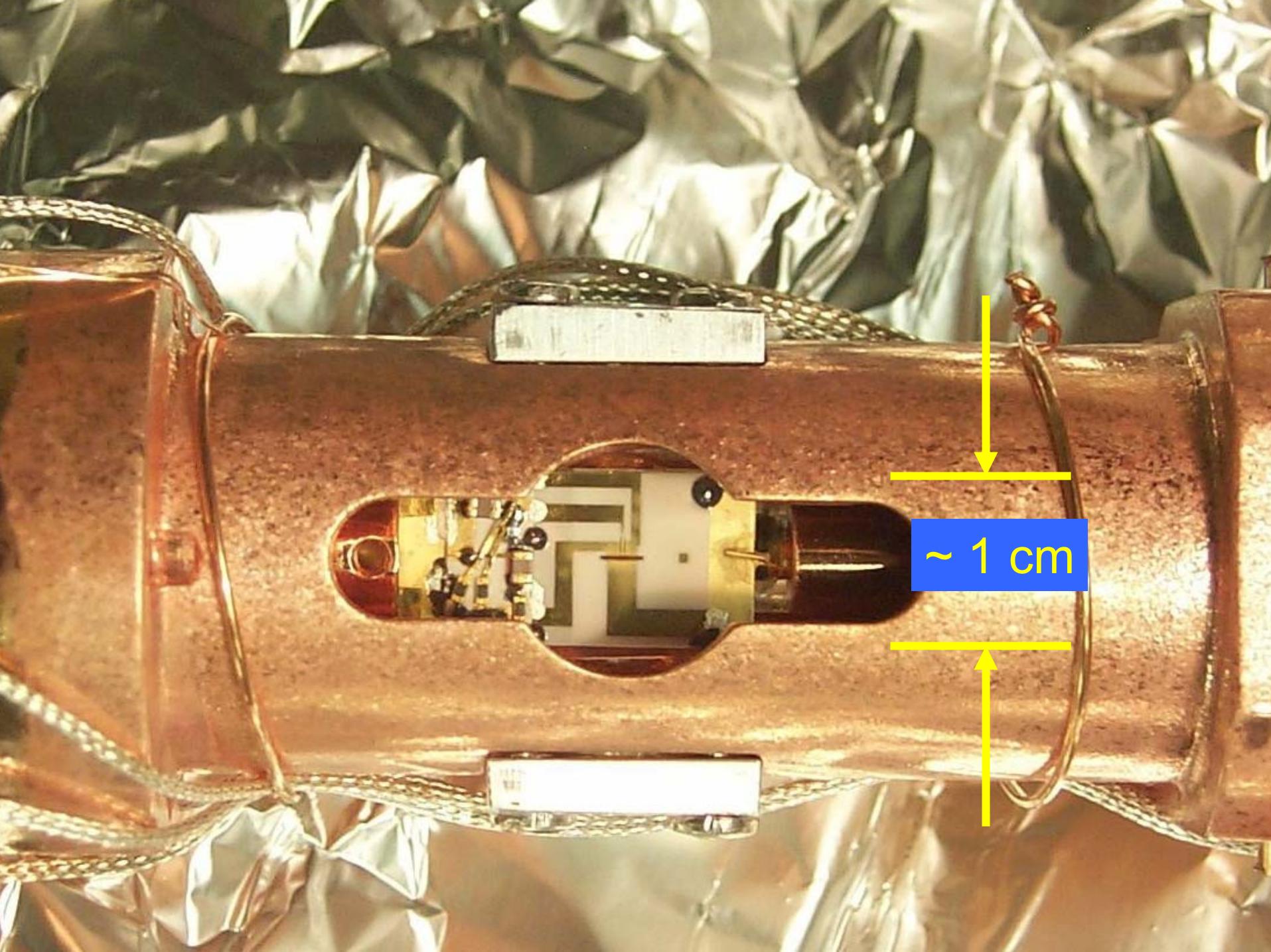




For ${}^9\text{Be}^+$, $V_0 = 500$ V, $\Omega_T/2\pi = 200$ MHz, $R \approx 200$ μm
 $\omega_{x,y}/2\pi \sim 6$ MHz, $q_{x,y} \sim 0.085$

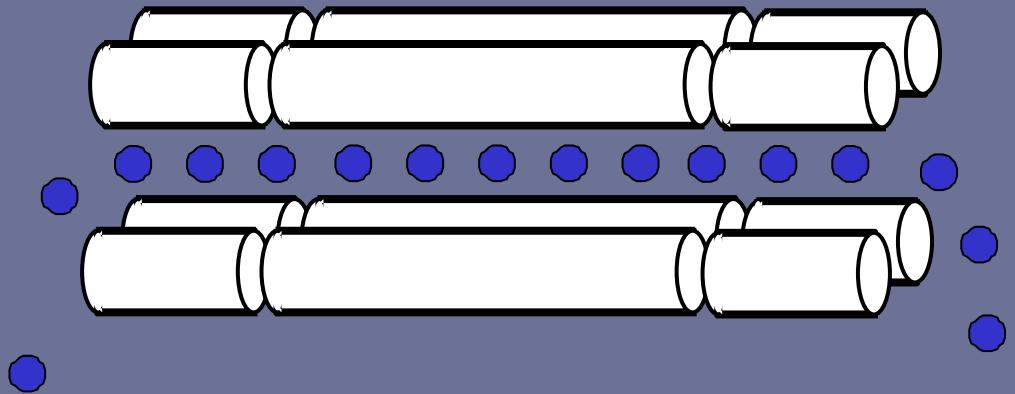


Chris
Myatt
et al.



$\sim 1 \text{ cm}$

Scale up ?

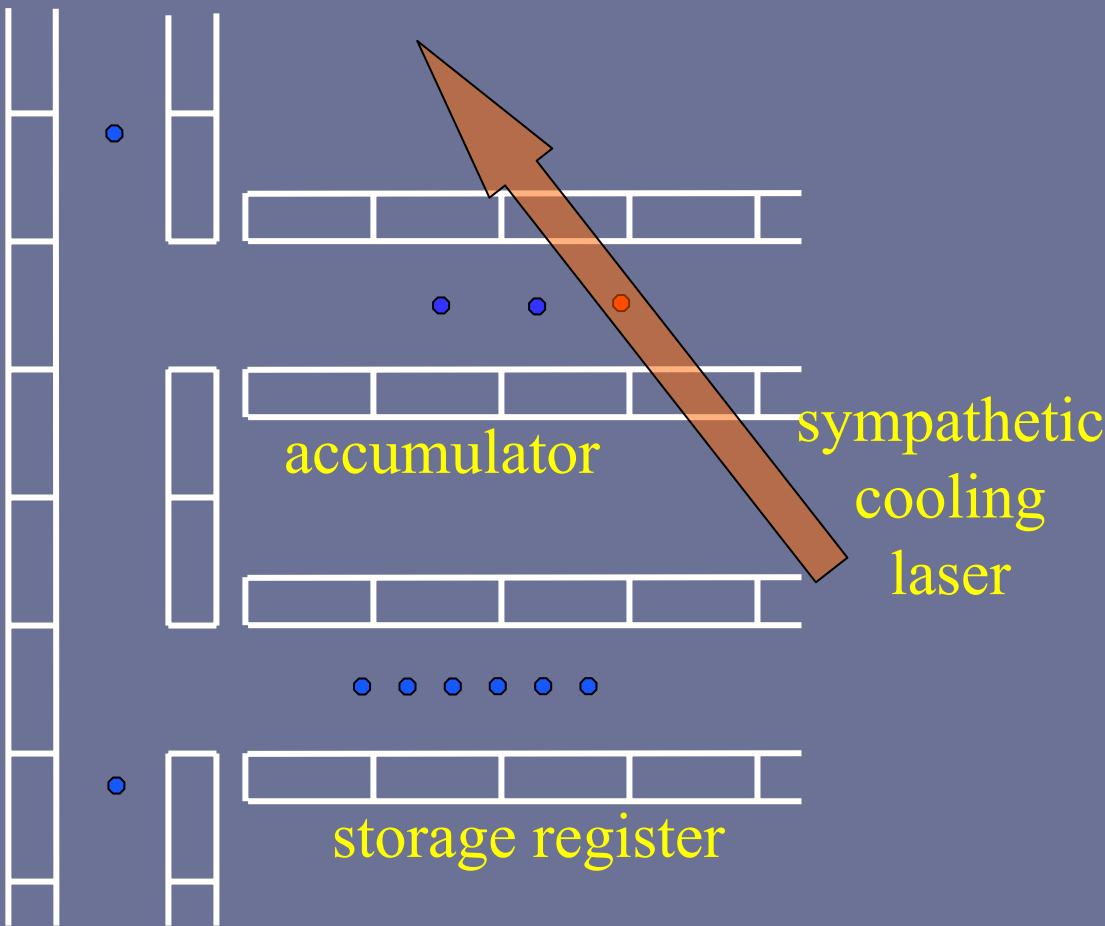


Problem:

- isolating one mode of motion for gates
- and/or cooling all modes sufficiently
- possible exceptions:
 - García-Ripoll, Zoller, Cirac, PRL **91**, 157901 (2003).
 - Šašura, Steane, PRA **67**, 062318 (2003).
 - Duan, L. -M., PRL **93**, 100502 (2004).
 - Zhu, Monroe, Duan, quant-ph/0508037

to additional accumulators
or storage registers

“Quantum CCD”



D. J. Wineland, et al., J. Res. Natl. Inst. Stand. Technol. **103**, 259 (1998).

D. Kielpinski, C. Monroe, and D. J. Wineland, Nature **417**, 709 (2002).

Other proposals: DeVoe, Phys. Rev. A **58**, 910 (1998); Cirac & Zoller, Nature **404**, 579 (2000); L.-M. Duan, B. Blinov, D. Moehring, C. Monroe, Quant. Inf. Comp. **4**, 165 (2004).

multiplexer chip

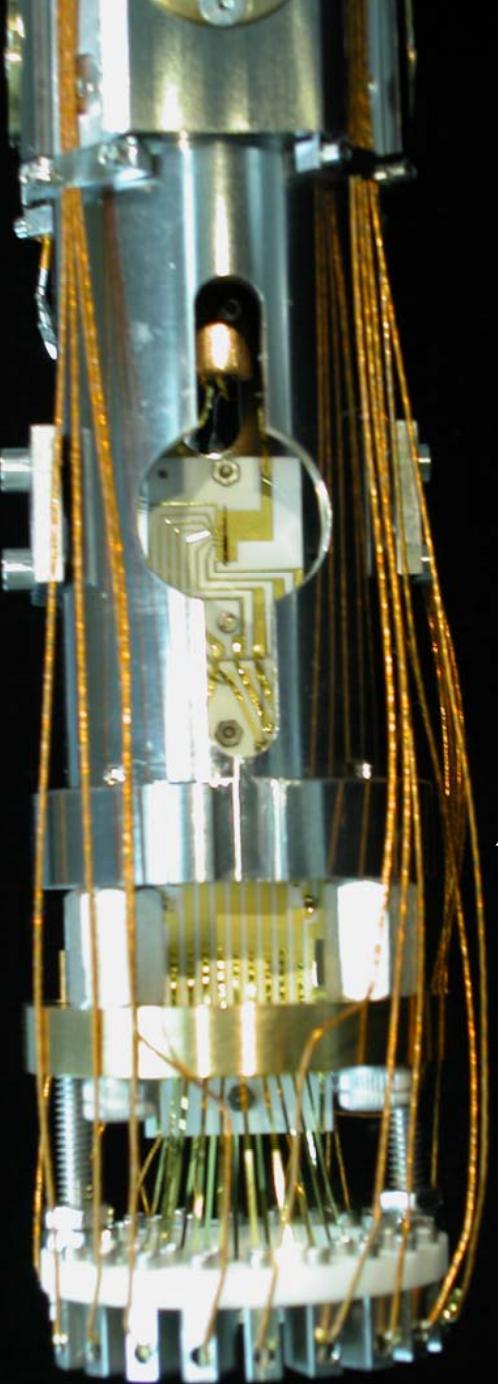
Mk 0.1: Mary Rowe *et al.* ('02)

Mk 0.2: Murray Barrett, John Jost *et al.* ('04)

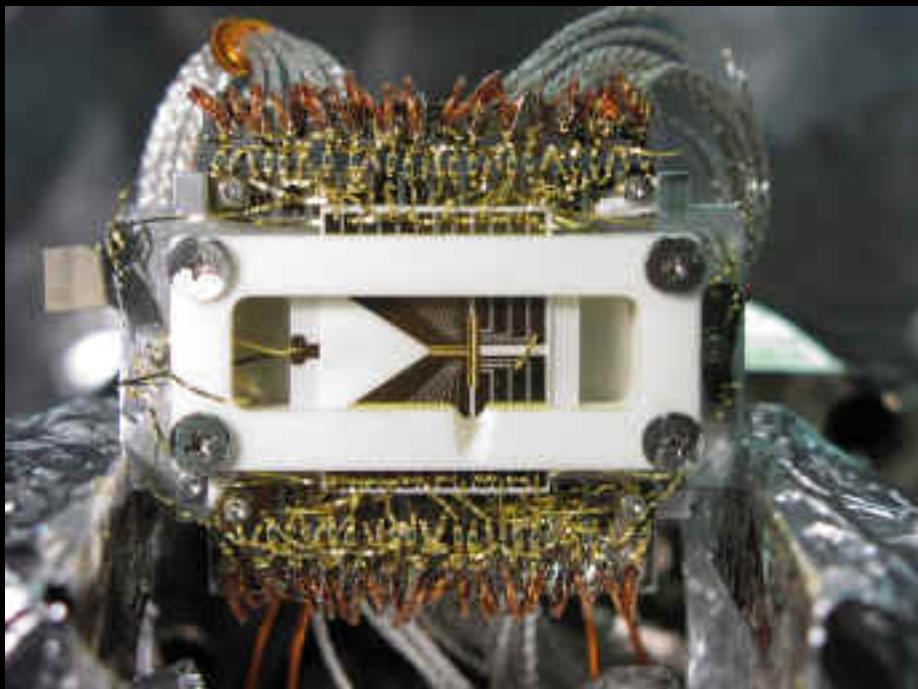
1.5 cm

200 μ m

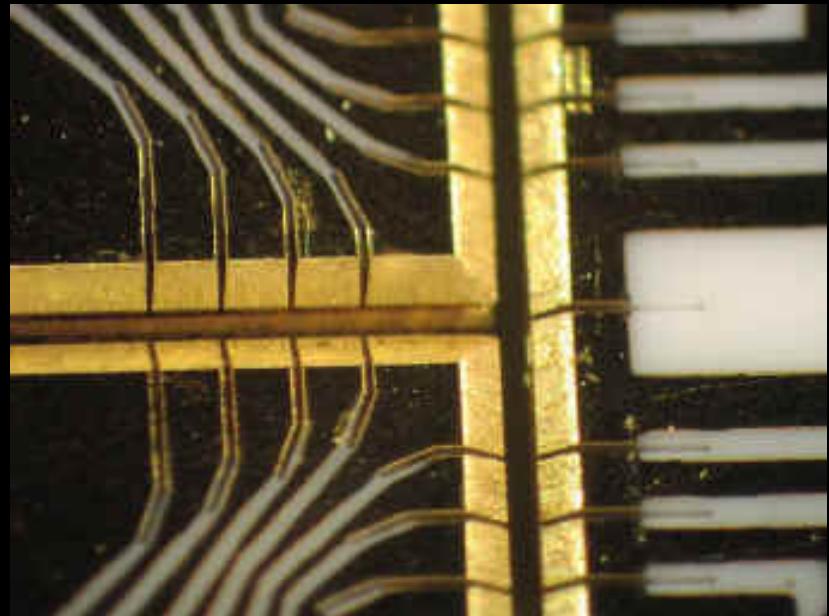
typical ion
spacing $\cong 2 \mu\text{m}$



Six zones,
 > 6 leads!



U. Michigan,
“T” trap
11 zones, more leads!

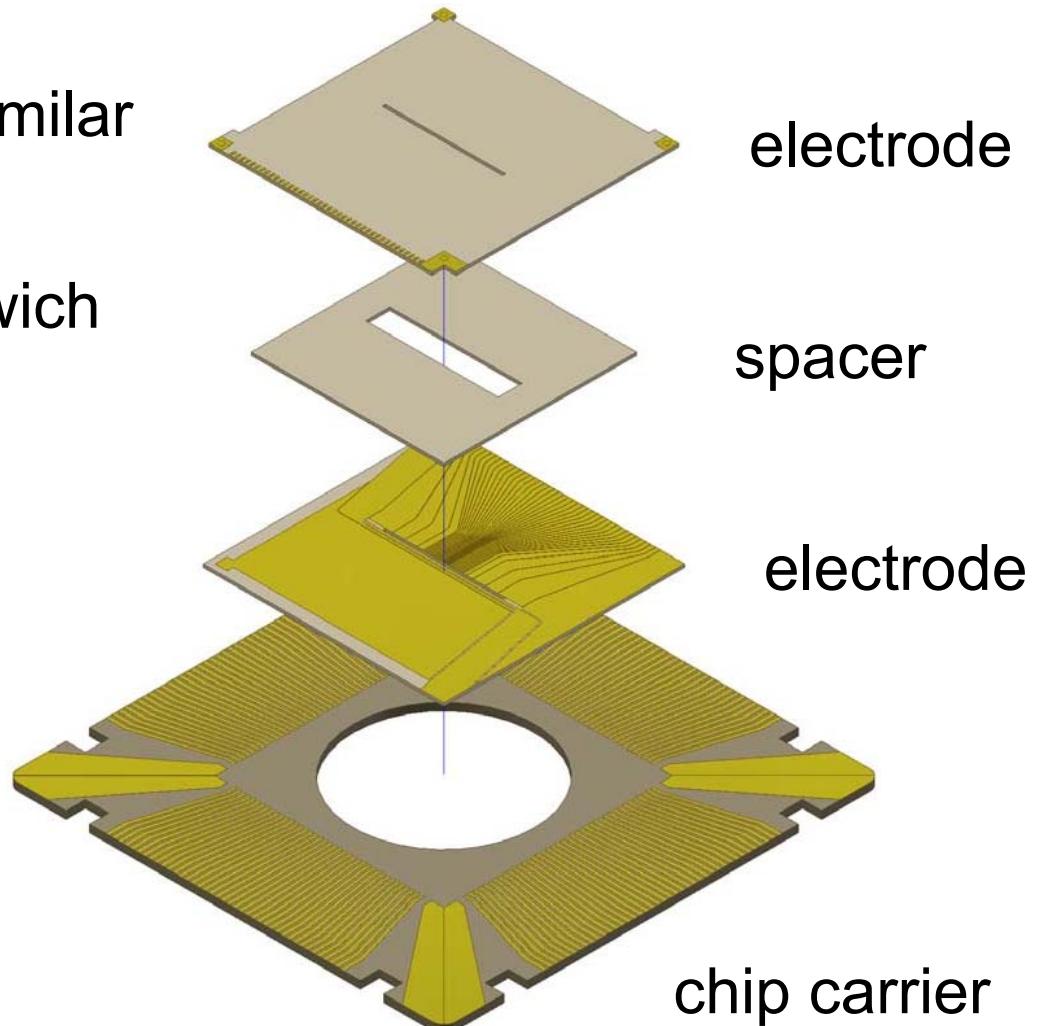


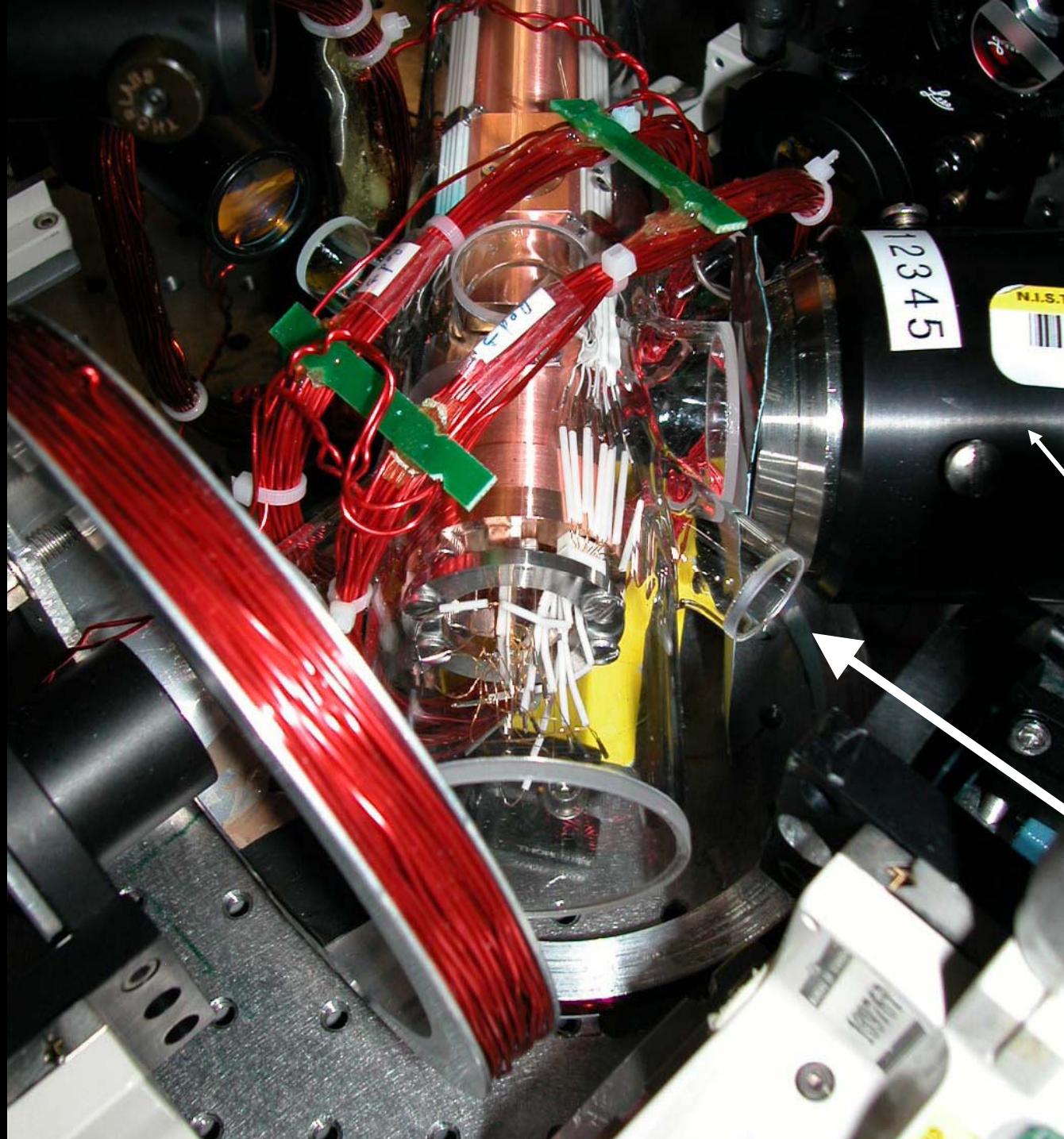
Innsbruck segmented trap (2005)

- electrode design similar as in 2004
- assembly as sandwich on chip carrier

work by

- ▶ Felicity Splatt
- ▶ Wolfgang Hänsel



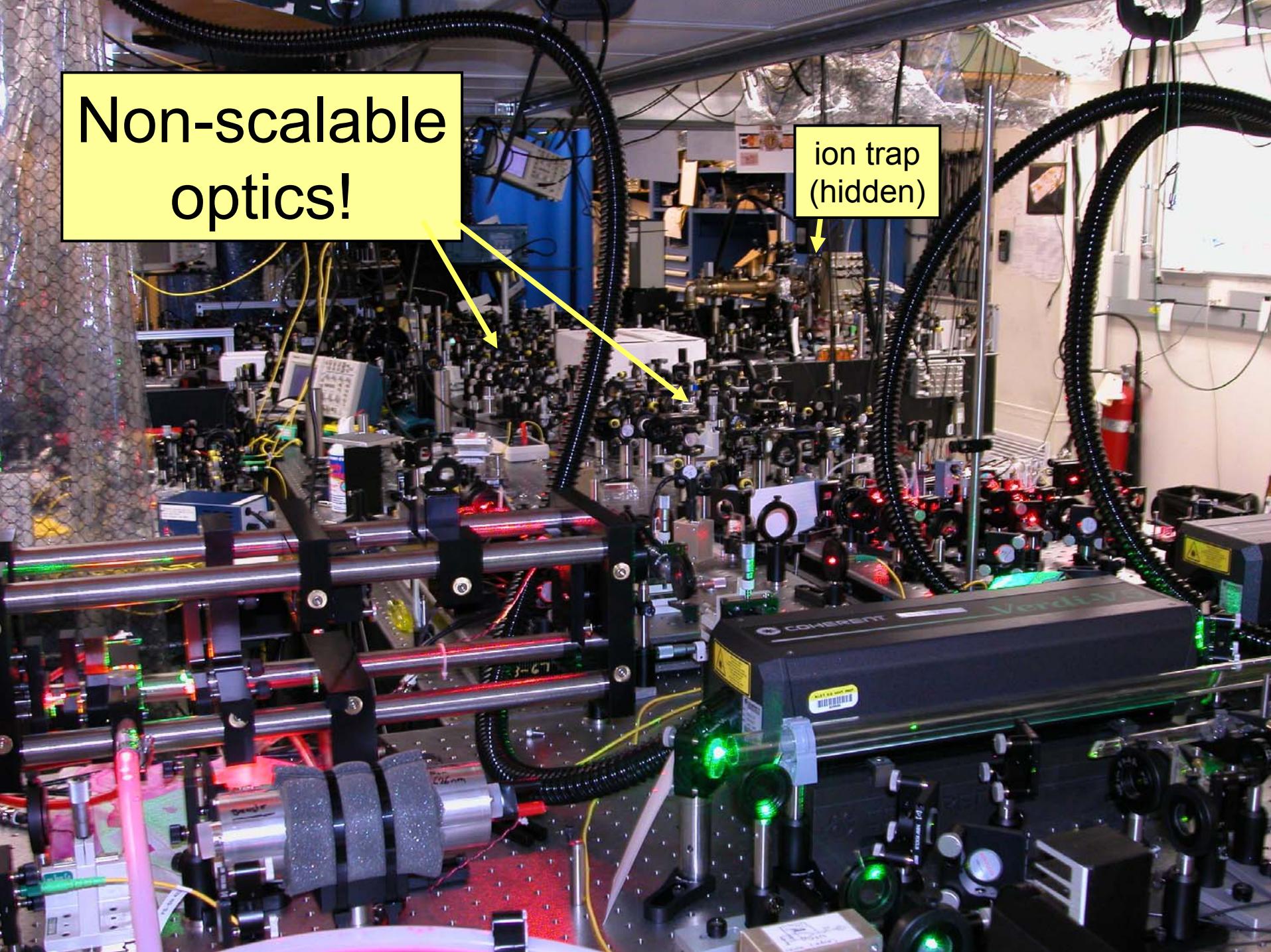


detection
optics

laser
beam

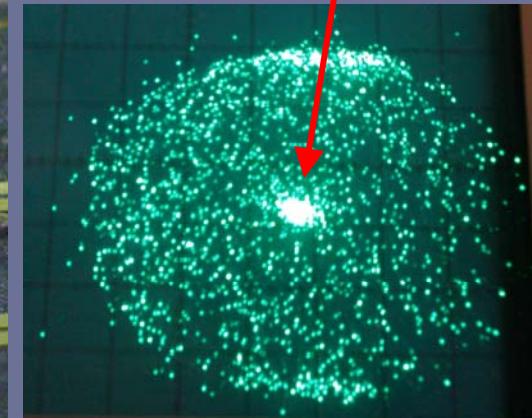
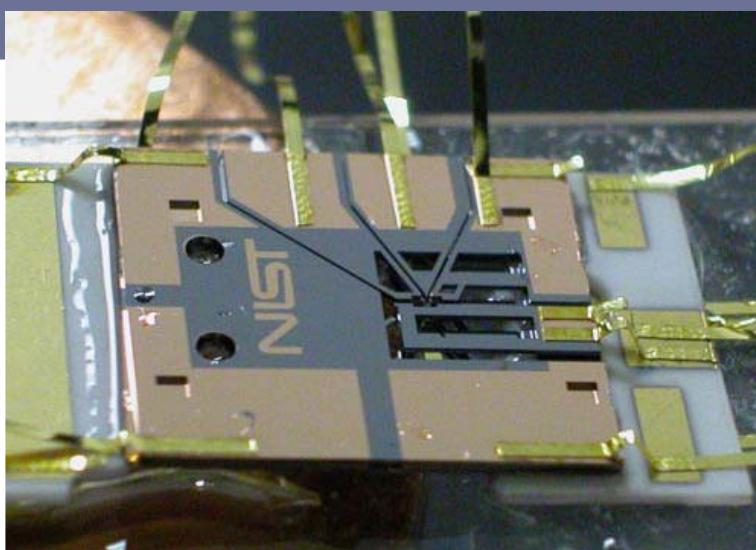
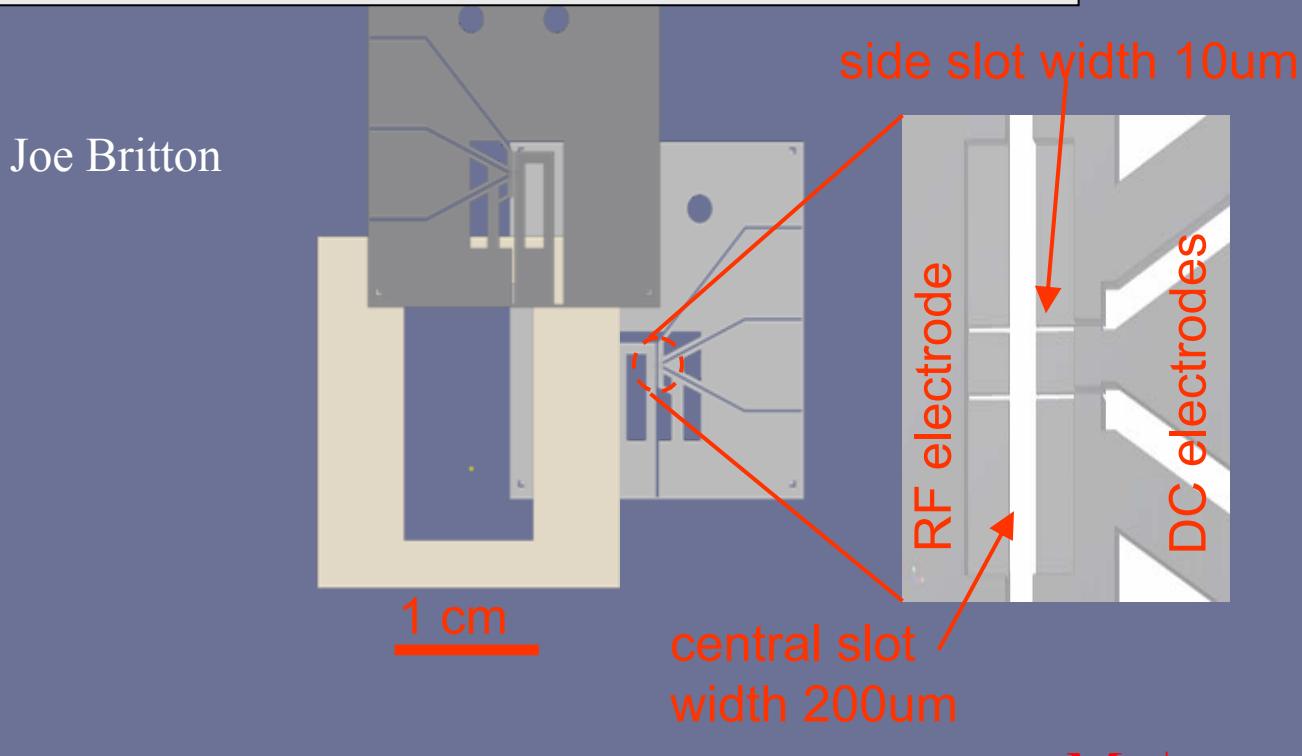
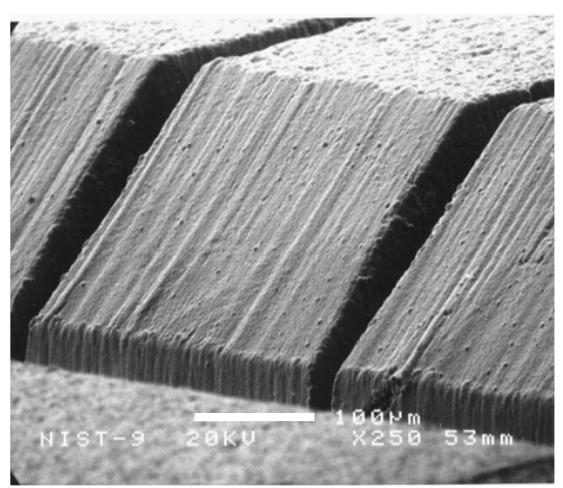
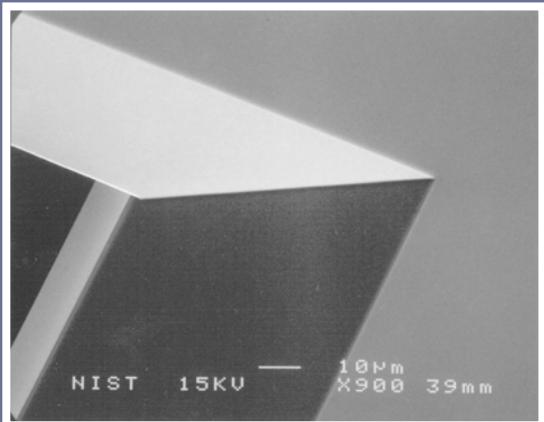
Non-scalable optics!

ion trap
(hidden)



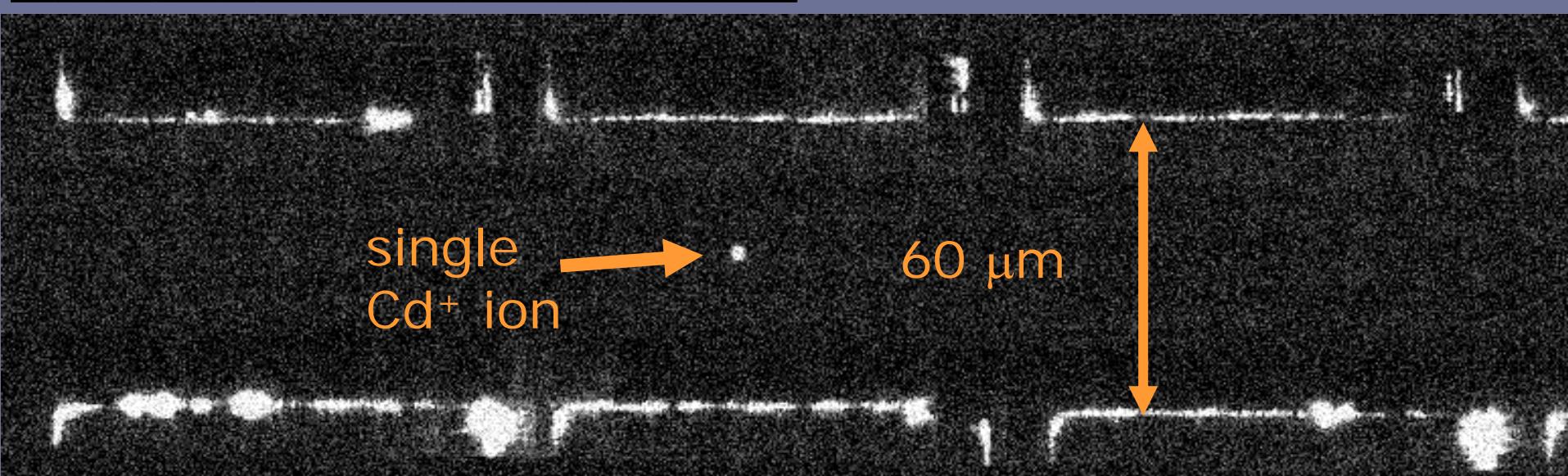
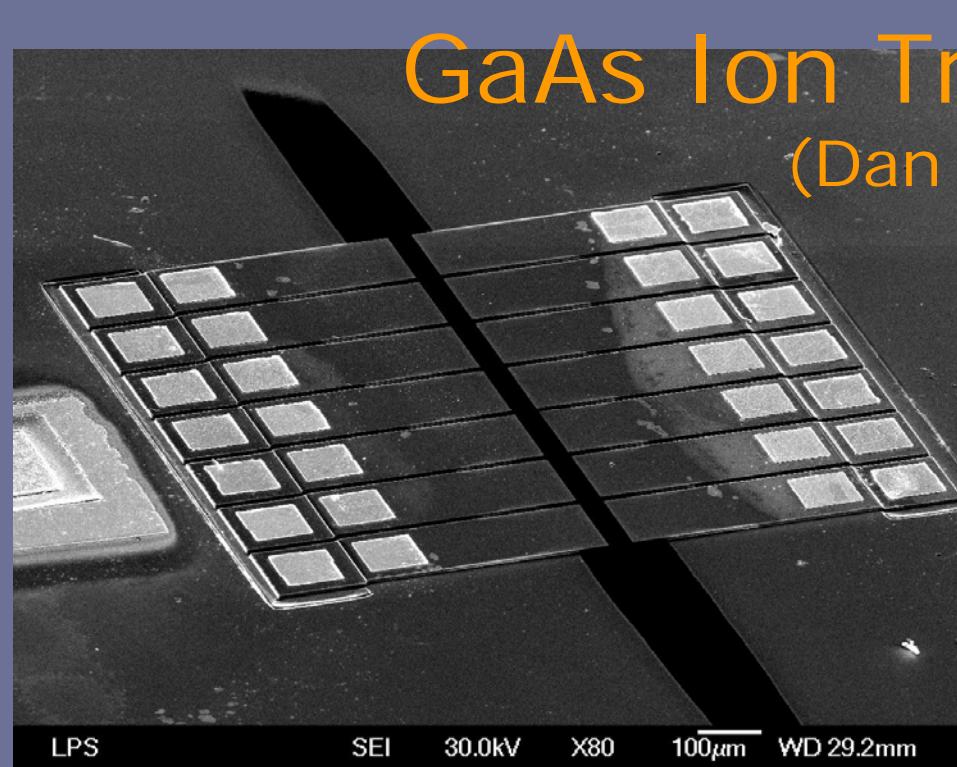
Scalable trapology? example: Boron-Doped Silicon Trap

- surface quality
- miniaturization
- scalable
- standard MEMS techniques



GaAs Ion Trap, U. Michigan

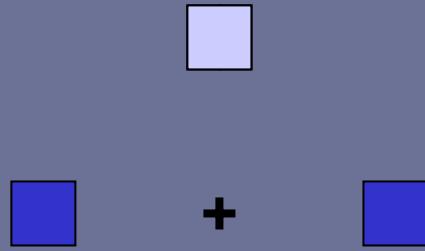
(Dan Stick *et al.*)



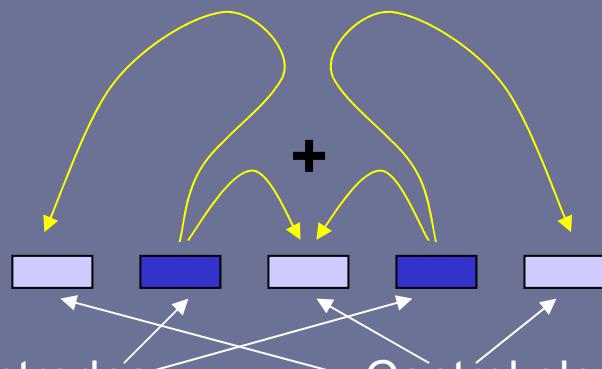
Surface-electrode trap:

(John Chiaverini *et al.*)

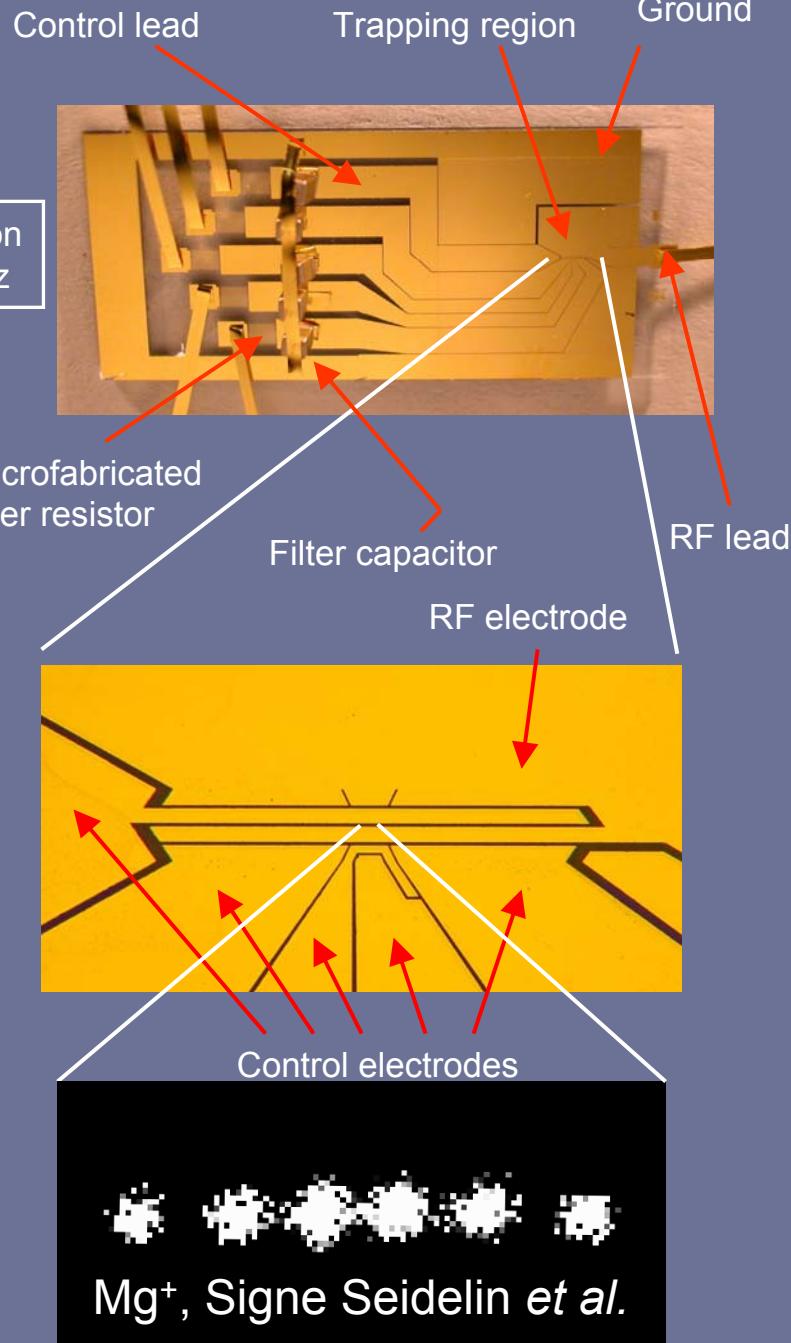
end view of linear quadrupole:



Field lines:

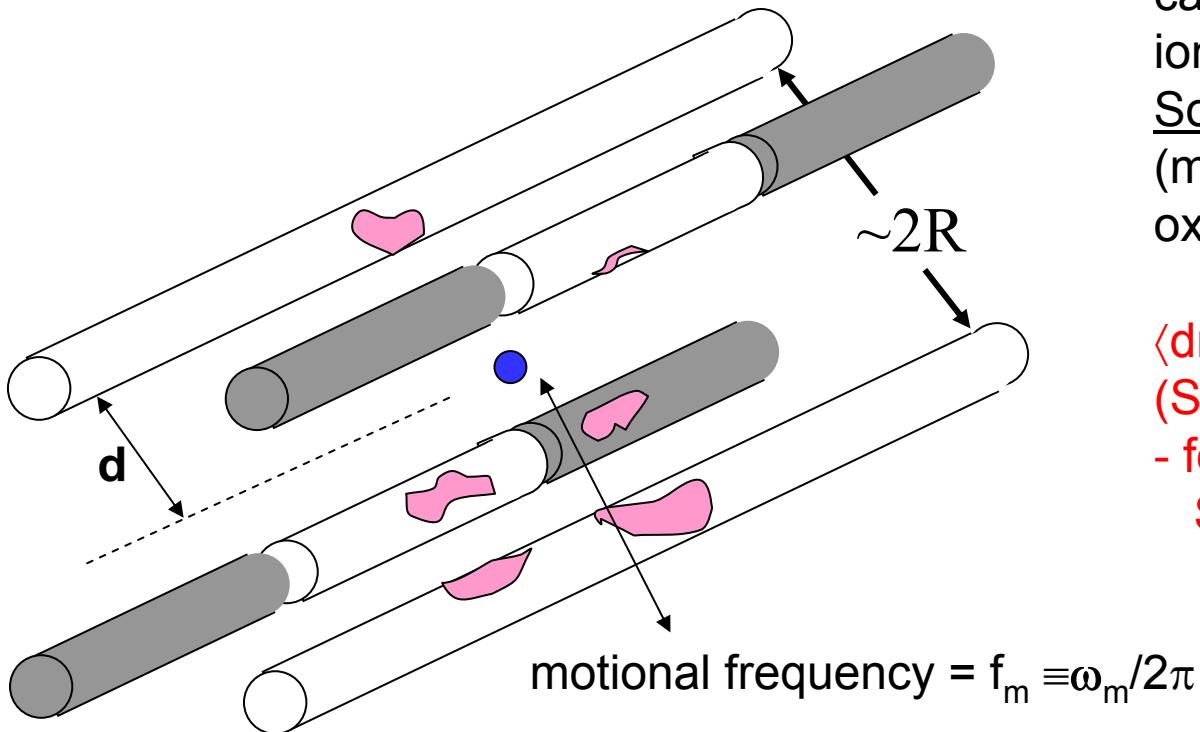


RF electrodes Control electrodes



Also, Ike Chuang's group

(some more) ion-trap realities

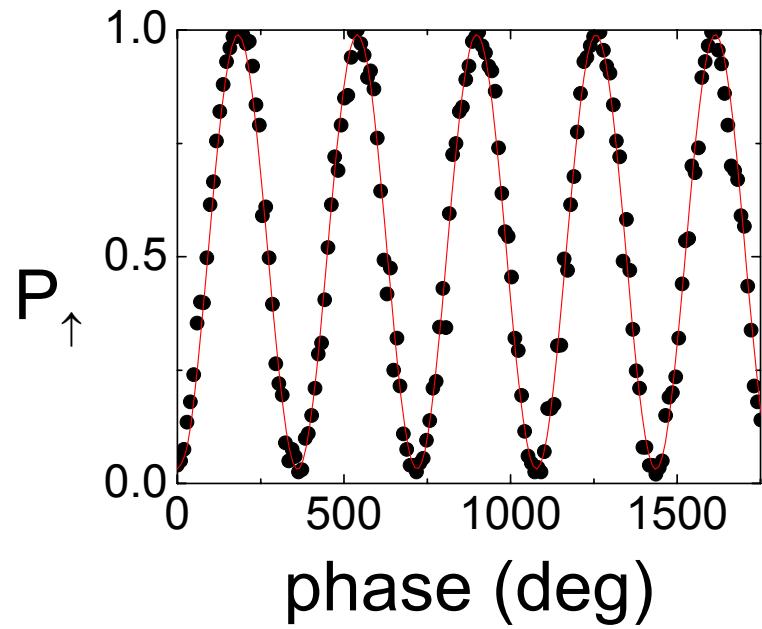
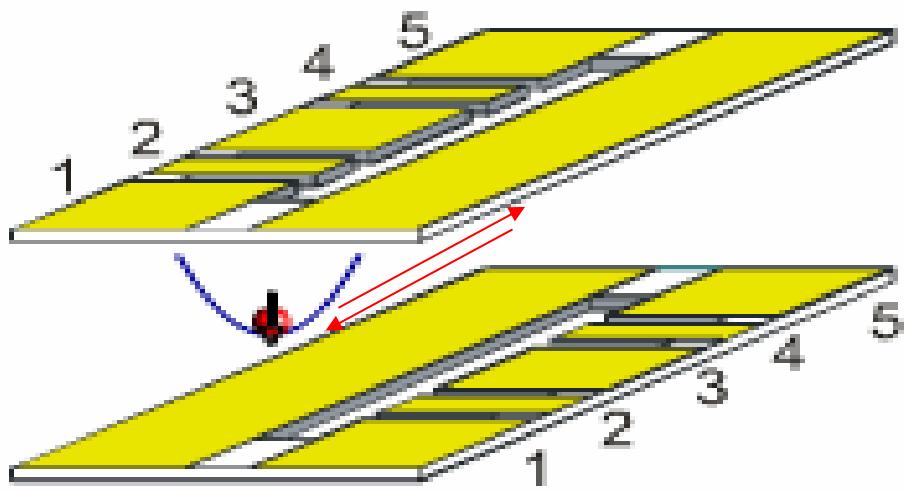


Fluctuating patch fields:
causes heating of
ion motion (at f_m)
Source: unknown!
(mobile electrons on
oxide layers,..... ??)

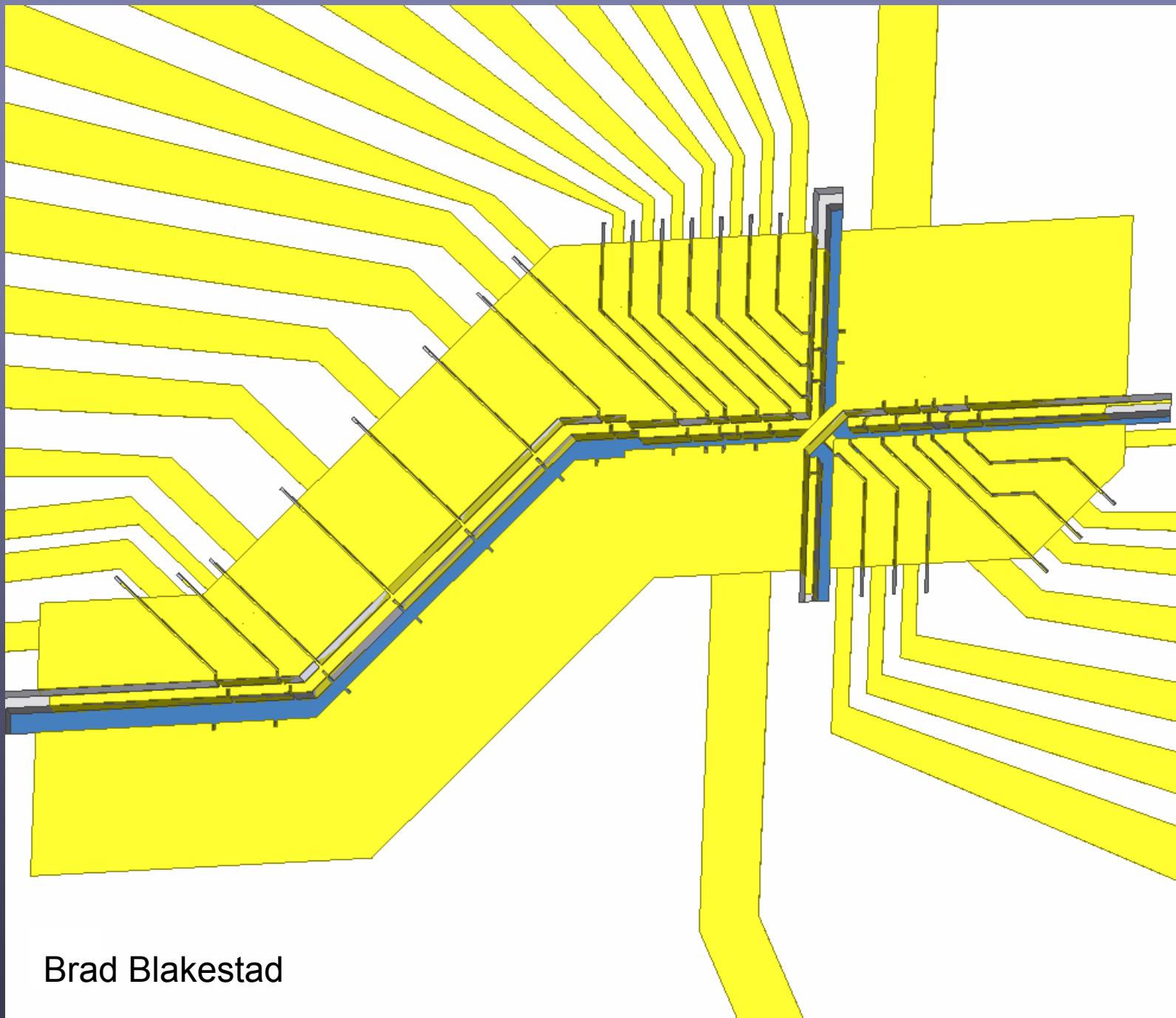
$\langle dn/dt \rangle \propto S_E/m\omega_m$
(S_E = E field spect. density)
- for patch size $\ll R$,
 $S_E \propto 1/R^4$

	R	$\langle dn/dt \rangle$
GaAs	$30 \mu\text{m}$	$10^6 \text{ s}^{-1}, f_m = 0.9 \text{ MHz}$
Au	$40 \mu\text{m}$	$5 \times 10^3 \text{ s}^{-1}, f_m = 2.8 \text{ MHz}$

$\Rightarrow S_E(\text{GaAs})/S_E(\text{Au}) \approx 100$
??

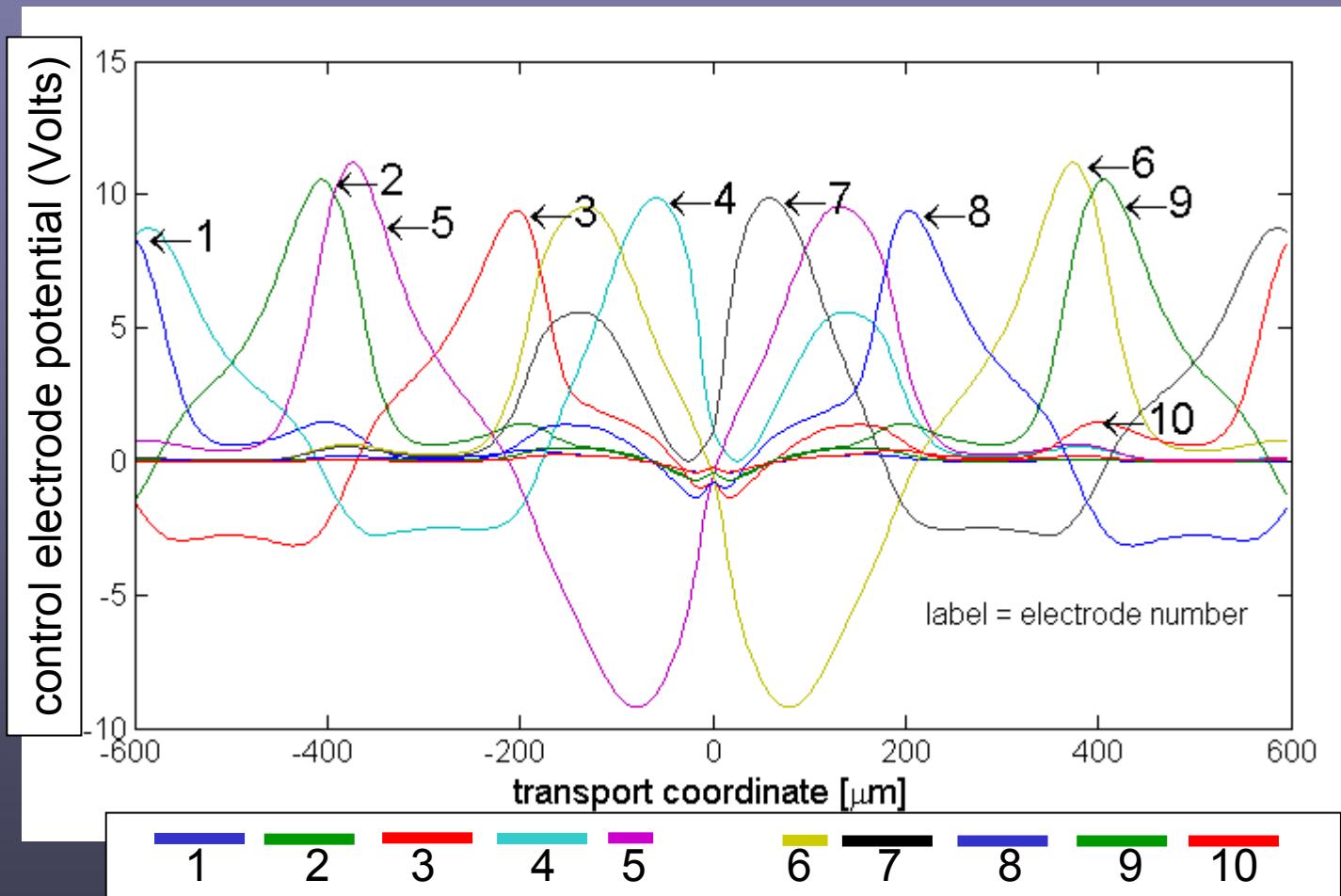


- $\tau(\text{transfer} \sim 1 \text{ mm}) \approx 25 \mu\text{s}$ (motion heating < 1 quantum)
- qubit coherence preserved during transfer (0.5 % measurement accuracy)



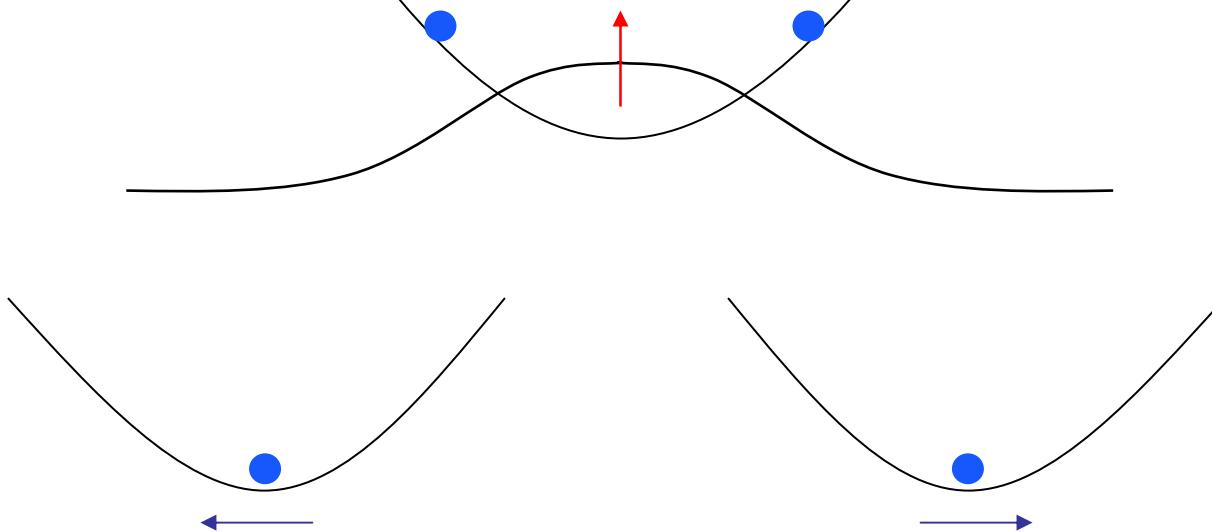
Brad Blakestad

Evolution of control electrode potentials for transport through “X” (Rainer Reichle)



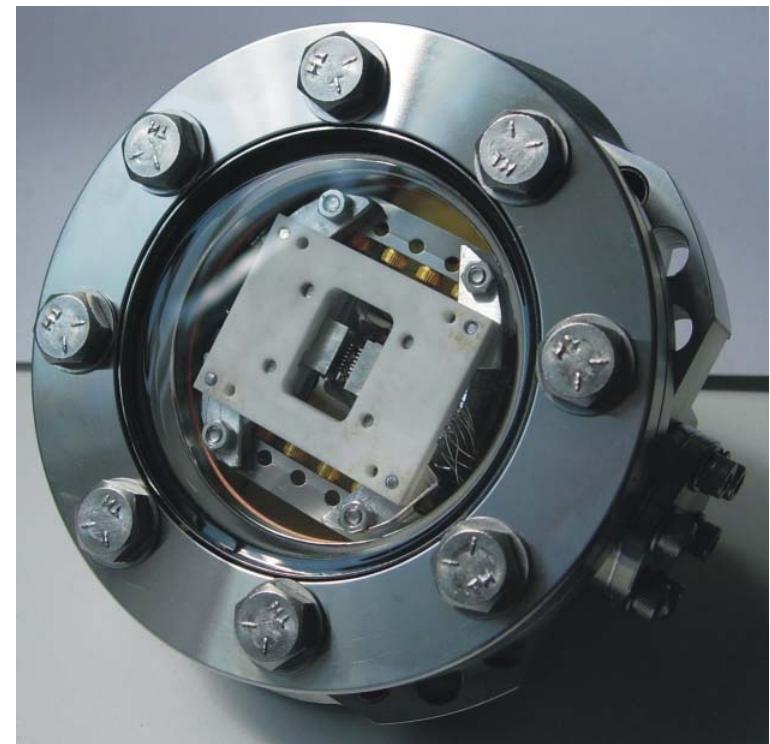
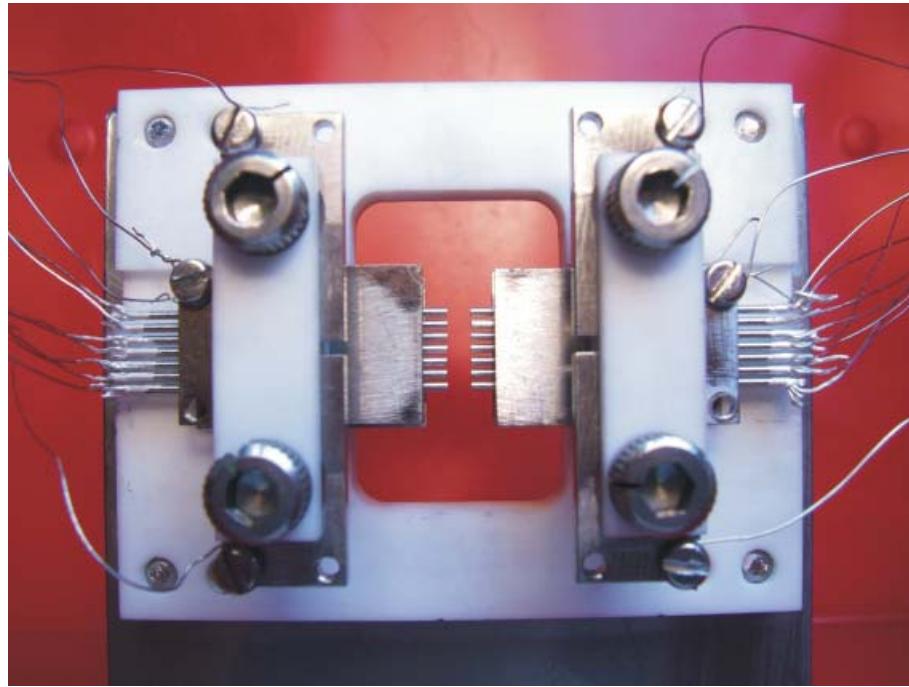
\ Ion separation:

/ See e.g., Home and Steane
quant-ph/0411102



separation faster with small dimensions; so is heating!

Oxford traps for separation studies



ion-electrode distance = 0.7 mm

trap-trap separation = 0.8 mm

test open design concept

Built by University of Liverpool (S.Taylor)

Ion trap score sheet:

Positives – they work! (at least for a few qubits)

- All Divincenzo criteria demonstrated (in separate experiments)
- Simple algorithms demonstrated
- Straightforward schemes for scaling

Problems for scaling:

- RF: stability, loss, ...
- control electrode potentials
 - stability, switching speed, crosstalk,...
 - lots of electrodes!
- fabrication
 - materials must be compatible with all requirements
 - scalable fab, low heating, bakeable,
 - number of zones $\gg 10^4$
 - multiple laser beams
 - multiple detection channels
 - crosstalk? (laser beams and control electrode potentials)
- heating – not understood yet, can we keep low enough? low temperature?